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RESEARCH ARTICLE

Spatial runoff estimation and mapping of potential water harvesting sites using GIS and Remote Sensing

Pavithra B N[1], K S Rajashekarappa[1] & Devappa[2*]

[1]Soil and Water Engineering, University of Agricultural Sciences, Gandhi Krishi Vigyana Kendra, Bengaluru 560 065, India

[2]Soil and Water Conservation Engineering, Agricultural Engineering College and Research Institute, Tamil Nadu Agricultural University, Coimbatore 641 003, India

*Email: devappa.phdswe2022@tnau.ac.in

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Abstract

The worsening of drought conditions has significantly increased water scarcity, notably impacting arid and semiarid regions globally. Consequently, effective runoff management has emerged as a critical challenge. Different maps were overlaid to identify appropriate locations for water harvesting structures, considering technical and social factors such as soil texture, slope gradient, land use/cover (LULC) and flow accumulation. Applications of remote sensing and GIS (Geographic Information System) were integrated to accomplish this goal. Designing water harvesting structures requires an accurate understanding of runoff from rainfall. Although direct field-level runoff assessment is beneficial, it is costly, time-consuming and labor-intensive. The precipitation data for runoff calculations were obtained from an automatic weather station installed within the study area, while soil and land use/cover data were sourced from the Rejuvenating Watersheds for Agricultural Resilience through Innovative Development (REWARD) project. The modified infiltration approach was utilized to store, analyze and estimate runoff depth, surface storage and runoff volume utilizing the GIS tools. The runoff volume for harvesting in 2019 was 0.62 MCM (Million cubic meters) and that in 2021 was 1.09 MCM. The suitable sites in the study area were identified 24.50% as suitable for contour bunds, 4.0% for staggered trenches, 5.14% for V-shaped ditches and 8.35% for continuous trenches. Additionally, water harvesting structures were proposed for the Integrated Mission for Sustainable Development (IMSD) guidelines, with 40.20% of the structures deemed suitable for farm ponds, 8.70% for check dams and 8.35% for percolation ponds.

Keywords

check dam; contour bund; farm pond; infiltration; GIS; RS; water harvesting

Introduction

Water is a critical resource, yet growing populations and the impacts of climate change increasingly threaten its availability. Shifting weather patterns have intensified water-related challenges, leading to prolonged droughts in some regions and unpredictable, intense rainfall in others, contributing to water scarcity and flooding (1, 2). Sustainable water resource management is essential to ensure water availability for agricultural, industrial and domestic needs. In this context, runoff estimation is crucial in assessing the potential for water harvesting (3-5). To crucial determination of surface water availability for collection, storage and future use.

The processes whereby rainfall becomes runoff are difficult to quantify and conceptualize (6, 7). Runoff refers to the portion of precipitation that flows over the land surface after infiltration, evaporation and storage demands of the landscape are met (8, 9). An accurate runoff runoff estimation is critical for designing water harvestings and conservation features such as percolation ponds, farm ponds, check dams, contour bunds and trenches (10-13). These structures mitigate the negative effects of excess runoff, including erosion and land degradation, while helping capture and store water that can be used during periods of low rainfall (14 -16). The assessment of rainwater demand and the identification of suitable locations for water-harvesting and groundwater recharge structures are crucial, particularly in irrigation command areas (17, 18).

Applications of geospatial information, such as geographic information systems (GISs) and remote sensing methods, deliver recent and valuable data at various scales (19). These technologies facilitate accurate runoff estimation and identification of suitable sites for water harvesting, as well as the implementation of soil and water conservation measures (20-22). Thus, researchers can analyze spatial rainfall patterns, topography, land use and soil characteristics to optimize site selection for water conservation measures (23-25).

Current research focuses on estimating runoff using the infiltration method. It also involves identifying suitable sites for constructing water harvesting structures and implementing soil conservation measures within the Niragantipalli micro-watershed. This study uses geospatial techniques to assess topographical, hydrological and land use characteristics to identify optimal sites for harvesting and conservation structures. This approach contributes to sustainable water management and aims to minimize erosion, improve agricultural productivity, ensure long-term water availability in the region.

Materials and Methods

Description of the study area

The investigation was conducted in the micro-watershed (WS -Code: 4C3G8d05), covering a total geographical area of 632 ha. This watershed is part of the Gollapalli sub watershed in the Eastern Dry Agro-climatic Zone of Karnataka, located in Chikkaballapura District, India. It lies between 13°46'17.36"N to 13°44'51.06"N latitude and 77°51'56.44"E to 77°53'19.97"E longitude, with an average elevation of 915 m above mean sea level. The elevation of the micro-watershed ranges from 763 m to 1059 m above mean sea level (MSL). The lowest elevation, 763 m, is located near the outlet, where a gauging station is positioned. In contrast, the highest elevation, 1059 m, is found over the hillocks in the upstream sections of the watershed. The location map of the micro-watershed is shown in Fig. 1.

To estimate runoff, the study utilized the modified infiltration excess method, developed under the REWARD project, as detailed in Fig. 3. According to Horton's principle, runoff occurs when rainfall exceeds the soil's infiltration capacity. However, this approach has been adopted to account for water retention within the field by incorporating bund length and bund area as additional parameters. This retained water during the runoff process within the field is termed runoff excess.

Runoff calculation involved categorizing soil mapping units based on texture and depth (Table 1) and estimating abstraction losses within the micro-watershed by determining bund length and bund area using Arc GIS software.

Average intensity = Rain fall depth / duration (Eqn.1)

Net instantaneous runoff rate (NIR mm/hr) = Average intensity (mm/hr) - Infiltration rate (mm/hr) (Eqn.2)

Potential Runoff = Net instantaneous runoff rate × Duration × Number of events (Eqn.3)

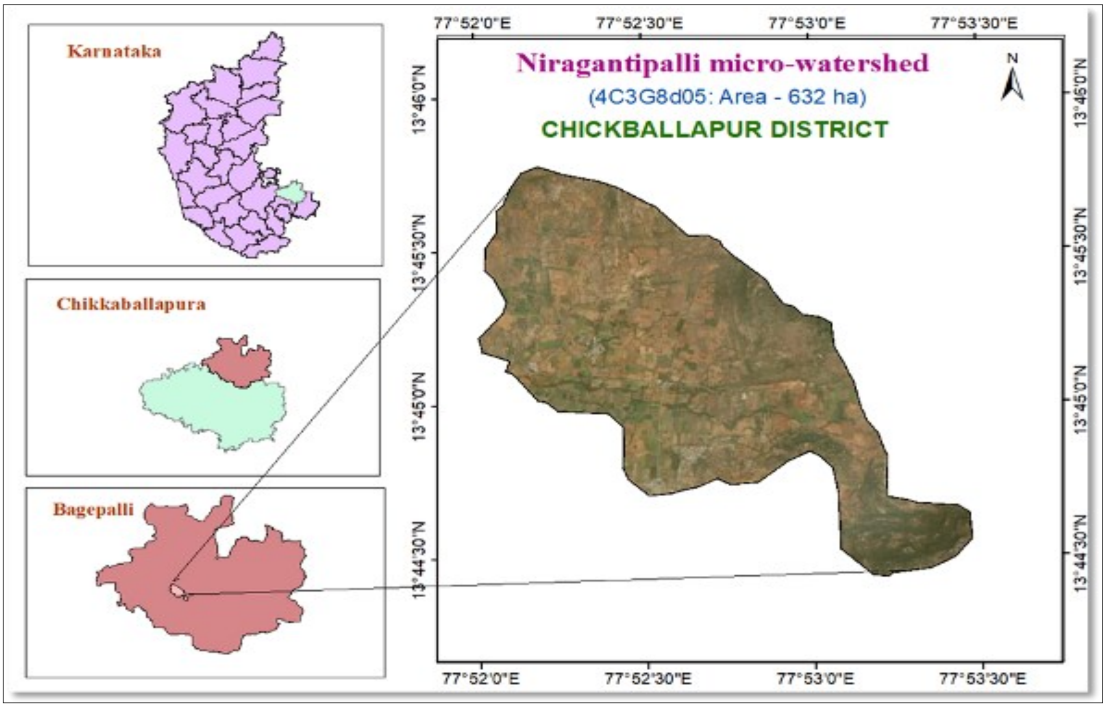

Fig. 1. Location map of the study area.

Maximum runoff retained (mm) =

$$\left[\frac{\text{Min bund length X Water spread area}}{\text{Area (1ha)}} \right] \quad \text{(Eqn. 4)}$$

Runoff excess = Potential runoff - Maximum runoff retained (Eqn.5)

Weight average of annual excess runoff $\left(\frac{mm}{hr} \right)$

$$= \left[\frac{\Sigma \text{ (Area of soil phase X Runoff depth)}}{\text{Total area (ha)}} \right] \quad \text{(Eqn. 6)}$$

The above procedure was applied for

Available runoff for harvesting =

Runoff excess - Environmental flow (Eqn. 7)

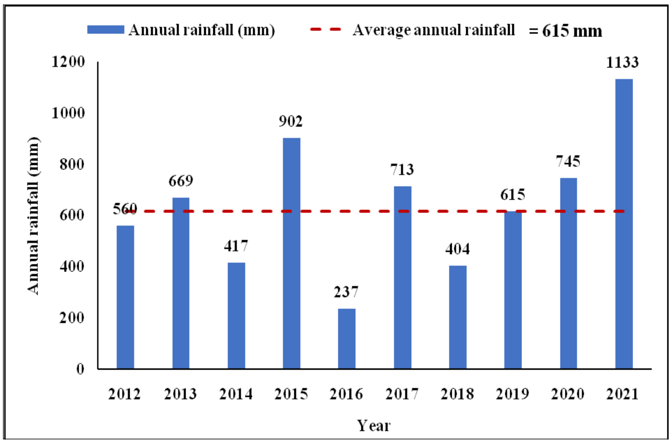

Fig. 2. Annual and average annual rainfall data of the Niragantipalli micro-watershed.

Table 1. Soil texture and corresponding soil phases of Niragantipalli micro-watershed

Sl. No	Soil Texture	Soil phases/Mapping units	Depth, cm
1	Clay	HLPmA1	50 - 75
		CDHmB1	75 - 100
		TSDmA1	100 - 150
2	Loamy sand	KTPbC2g1	50 - 75
		MHHbC2	75 - 100
		JDGbD2g1	100 - 150
		HLKbB1	
3	Sandy clay	BSRiB1g1	75 - 100
		HDHiA1	
		CDHiA1	100 - 150
		MRDiB1	> 150
4	Sandy clay loam	HTIhA1	50 - 75
		HTIhB1	
		MHHhC2g1	75 - 100
		CDHhB1g1	100 - 150
		BDKhC2g1	> 150
5	Sandy loam	KNHcC2g1	25 - 50
		KTPcC2g1	50 - 75
		HTIcB1g1	
		TDHcC2g1	
		CKMcC2g1	51-100
		HDHcC2	
		HDHcC2g1	
		HDHcC2g2	
		HLKcC2	>150

all soil textures and land uses within the micro-watershed by considering essential parameters such as soil texture, infiltration rates, abstraction losses, slope and environmental flow requirements. In this study, runoff was calculated using 12 years of rainfall data. From this dataset, two years were selected for detailed runoff analysis, namely 2021 (maximum rainfall) and 2019 (average rainfall), as shown in Fig. 2. The infiltration rates of cultivated and uncultivated land for accurate runoff calculations are detailed in Table 2 and Table 3.

The available runoff water can be effectively harvested and conserved by identifying suitable structures such as farm ponds, recharge percolation tanks and check dams. These structures were recommended within the watershed based on IMSD guidelines, as shown in Table 4 and Table 5. Conservation measures such as contour bunds, graded bunds, continuous contour trenches, staggered trenches and V-ditches are recommended to reduce soil erosion and enhance water retention. These measures were suggested using IMSD guidelines and GIS techniques (26,27,28). To locate suitable sites, various maps were prepared, including soil texture, permeability, runoff, slope, land use/cover maps and stream order maps. These maps, shown in Fig. 4 to Fig. 8, support selecting appropriate structures.

Results

This study assessed runoff estimation from both cultivated and uncultivated land using a modified infiltration method, revealing that the total available water for harvesting was 0.61 MCM in 2019 (an average rainfall year) and 1.09 MCM in 2021 (a year of maximum rainfall) illustrated in Table 6. The runoff water availability under different soil conditions is presented in Fig. 9 and Fig. 10 for 2019 and 2021, respectively. The results indicate that this runoff can be effectively conserved through appropriate water harvesting structures tailored to site-specific hydrological characteristics (29). The spatial analysis, aided by Remote Sensing (RS) and Geographic Information System (GIS) techniques, identified that 40.2% of the study area is suitable for farm ponds, 8.7% for check dams and 10% for percolation ponds (Table 7 and Fig. 11). Check dams are ideally located on second and third-order streams in micro-watersheds, covering approximately

Table 2. Infiltration rate (mm/hr) of cultivated land

Soils	Slope			
	A (0 - 1%)	B (1 - 3%)	C (3 - 5%)	D (5 - 10%)
Loamy sand (b)	30	28	26	20
Sandy loam (c)	22	20	18	14
Sandy clay loam (h)	16	14	10	6
Sandy Clay (i)	14	12	9	5
Clay (m)	10	9	5	3

Table 3. Infiltration rate (mm/hr) of uncultivated land

Sl. No	Class	Infiltration rate
1	Forest	8
2	Hill	1
3	Scrub land	3
4	Farmland	1

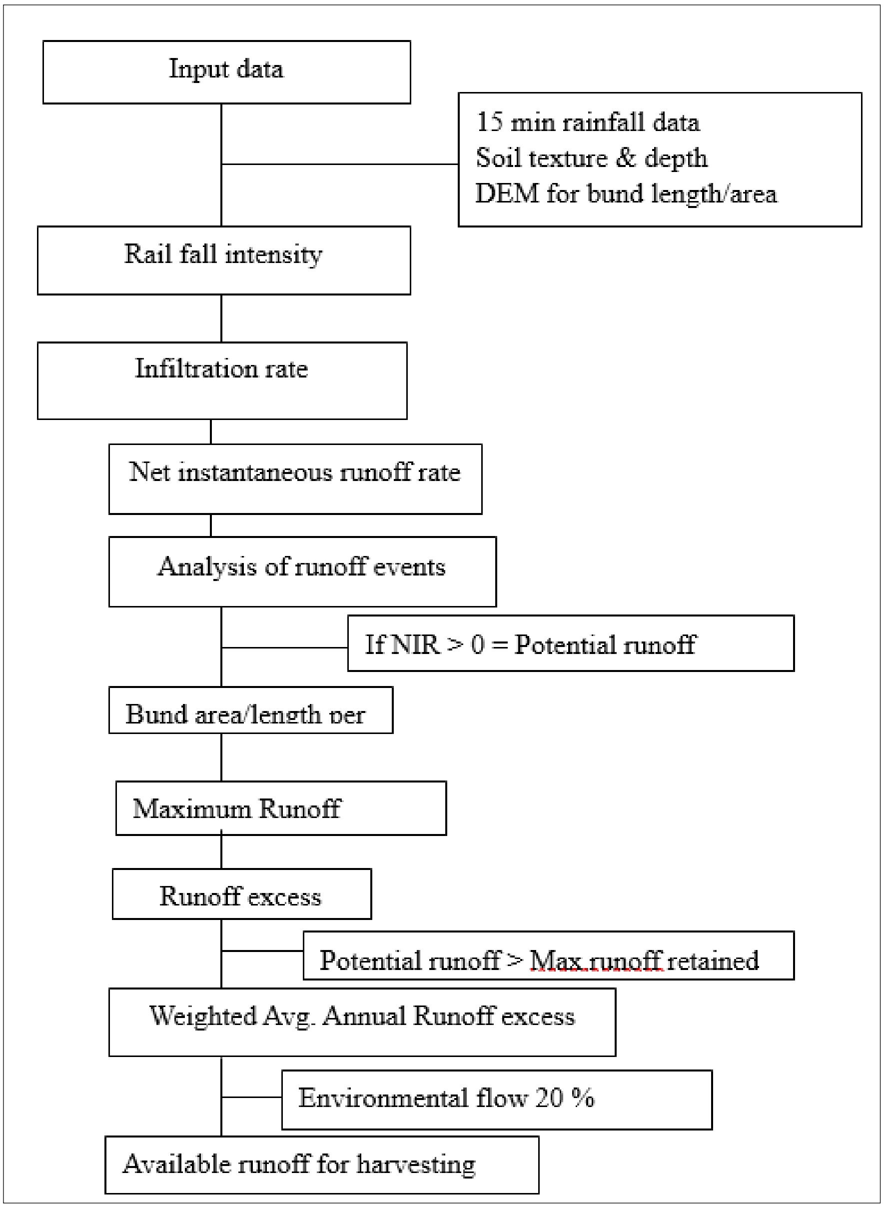

Fig. 3. Flow chart for runoff estimation.

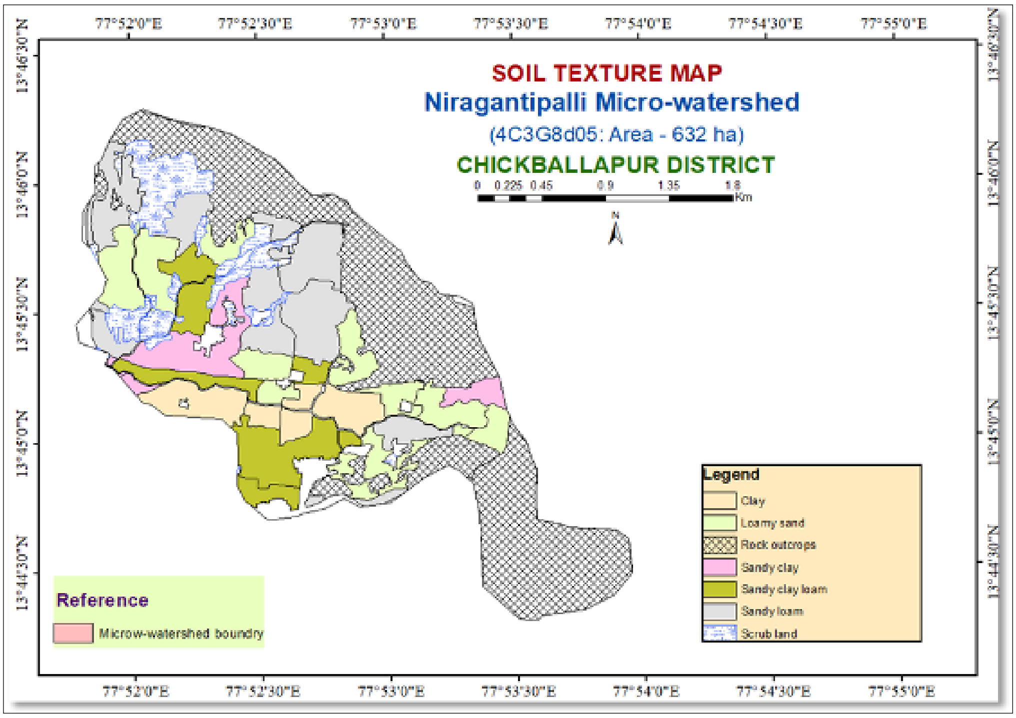

Fig. 4. Soil texture map of the Niragantipalli micro-watershed.

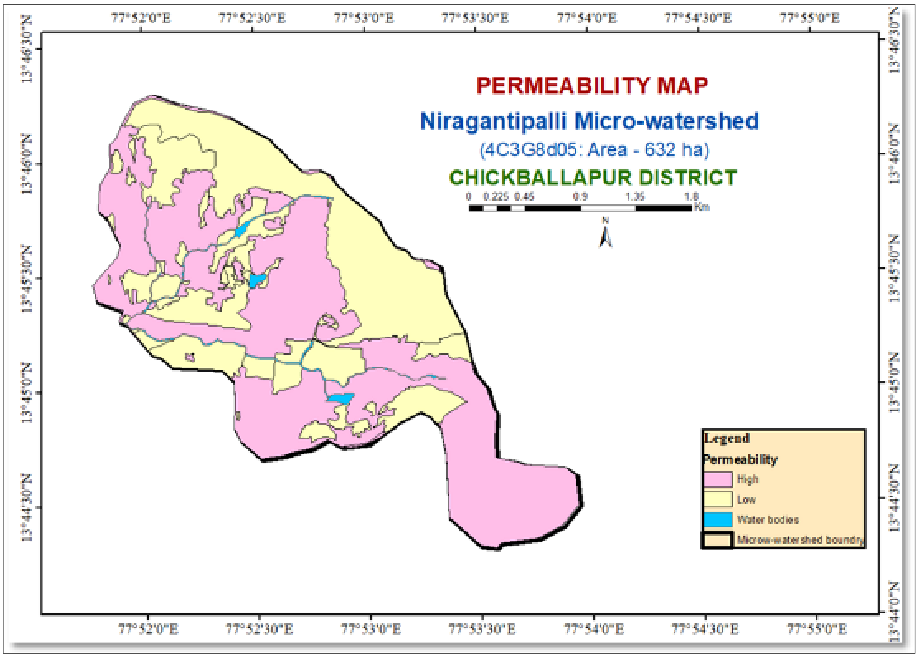

Fig. 5. Permeability map of the Niragantipalli micro-watershed.

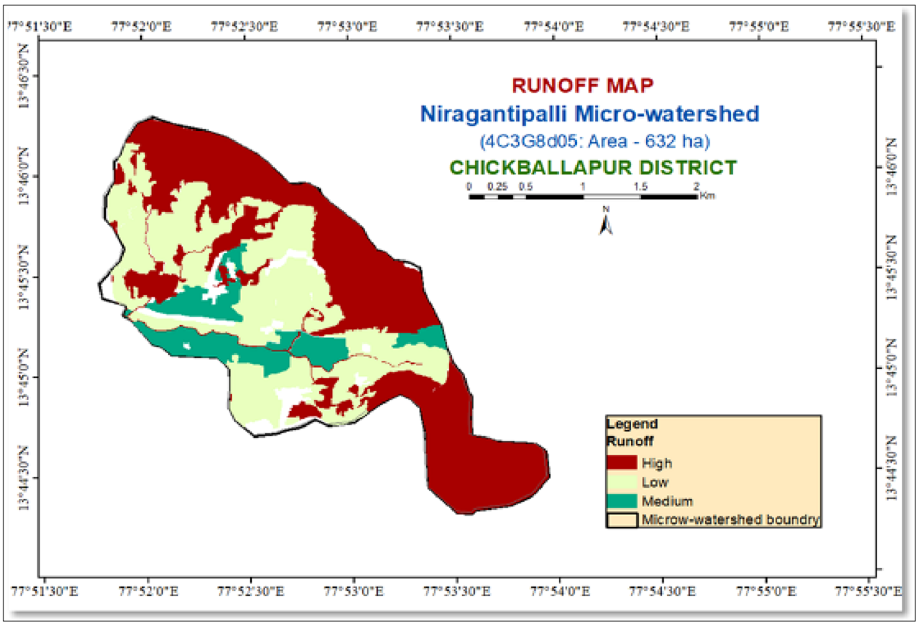

Fig. 6. Runoff map of the Niragantipalli micro-watershed.

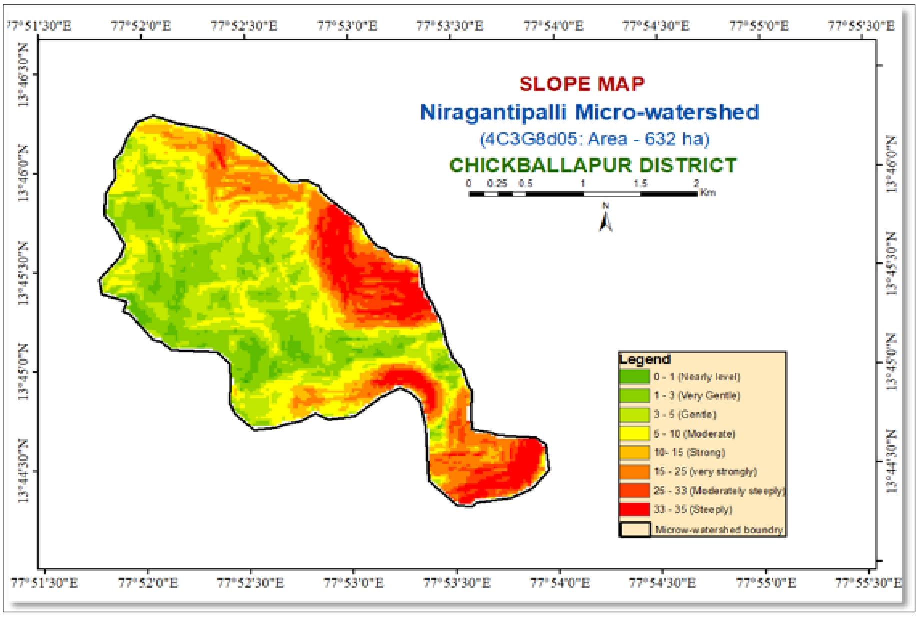

Fig. 7. Slope map of the Niragantipalli micro-watershed.

Table 4. IMSD criteria for the selection of suitable sites for water harvesting and structures

Structure	Slope (%)	Permeability	Runoff	Stream Order	Catchment Area (ha)
Farm Pond	0-5	Low	Medium/High	1	1-2
Check Dam	<15	Low	Medium/High	1-4	>25
Percolation Pond	<10	High	Low	1-4	25-40

Table 5. IMSD criteria for the selection of different soil and water conservation measures

Type of Structure	Rainfall in (mm)	Slope (%)	Land use	Soil permeability
Contour bund	<700	<6	Agricultural land	Medium to highly permeable soils
Graded bund	>700	2-8	Agricultural land	Less Permeable soils
Contour continuous trench	400-1200	10-30	Open scrub or Wasteland	Medium to highly permeable soils
Staggered trench	400-1200	10-30	Open scrub or Wasteland	Medium permeable soils
V-shaped ditch	<800	Up to 15	Open scrub or Wasteland	Medium permeable soils

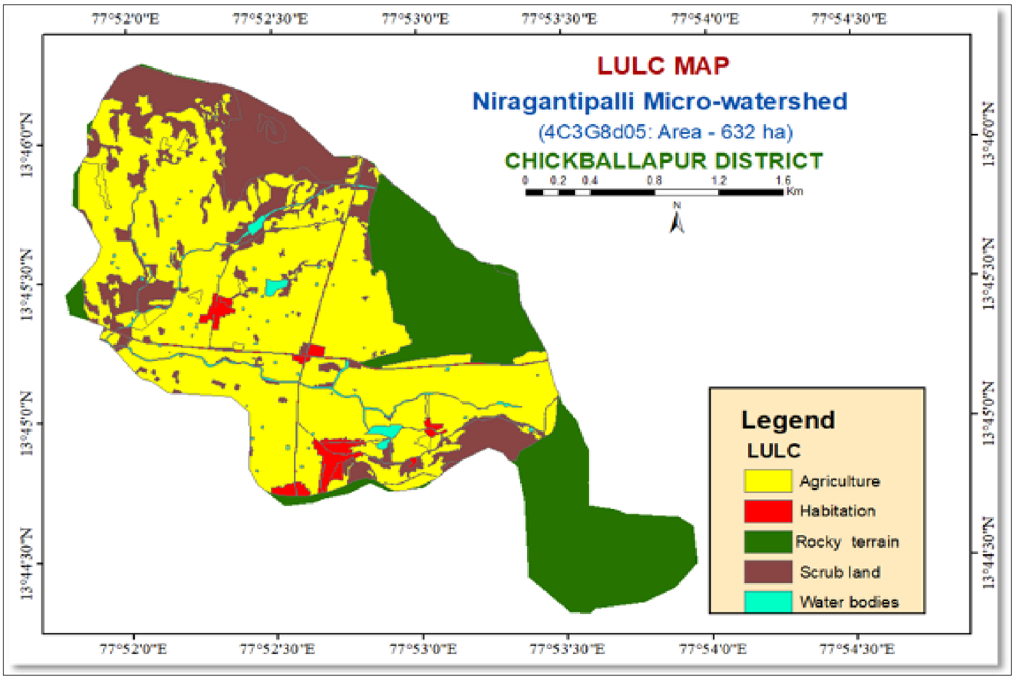

Fig. 8. LULC map of the Niragantipalli micro-watershed.

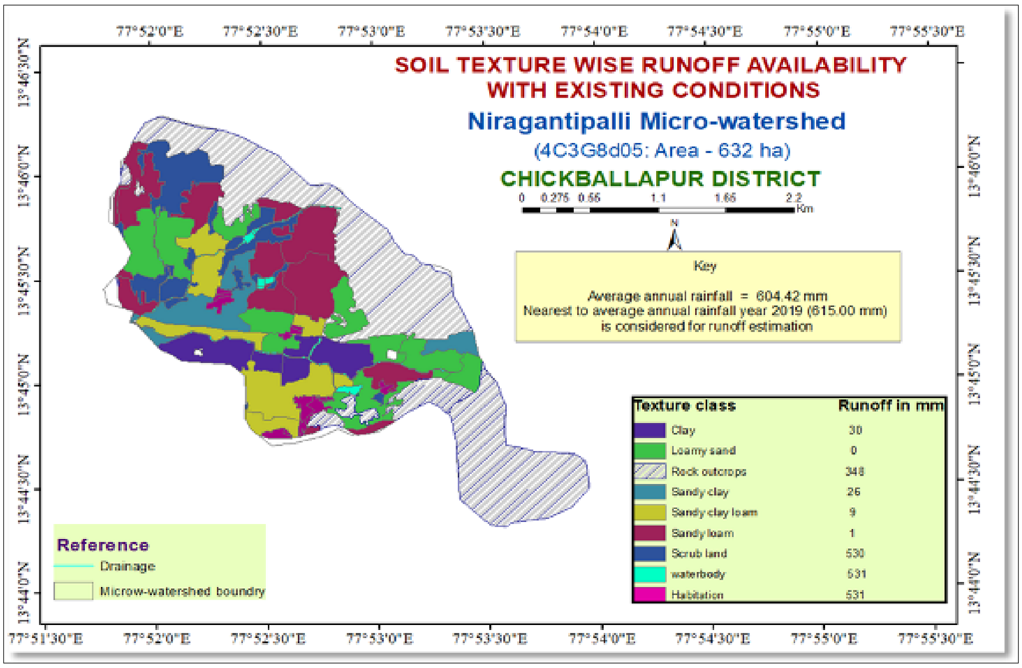

Fig. 9. Variations in runoff availability with existing conditions of Niragantipalli micro-watershed during 2019.

Table 6. Average and maximum annual runoff distribution in the Niragantipalli micro-watershed

Sl. No.	Particulars	Micro-watershed runoff distribution	
		Average annual rainfall (2019)	Maximum rainfall (2021)
1	Area. Ha	632	632
2	Total rainfall (mm)	615	1133
3	Total potential runoff (mm)	174	293
4	Runoff excess, mm	122	215
5	Environmental flow (mm)	24	43
6	Available runoff for harvesting (mm)	97	172
7	Available runoff volume for harvesting (MCM)	0.62	1.09

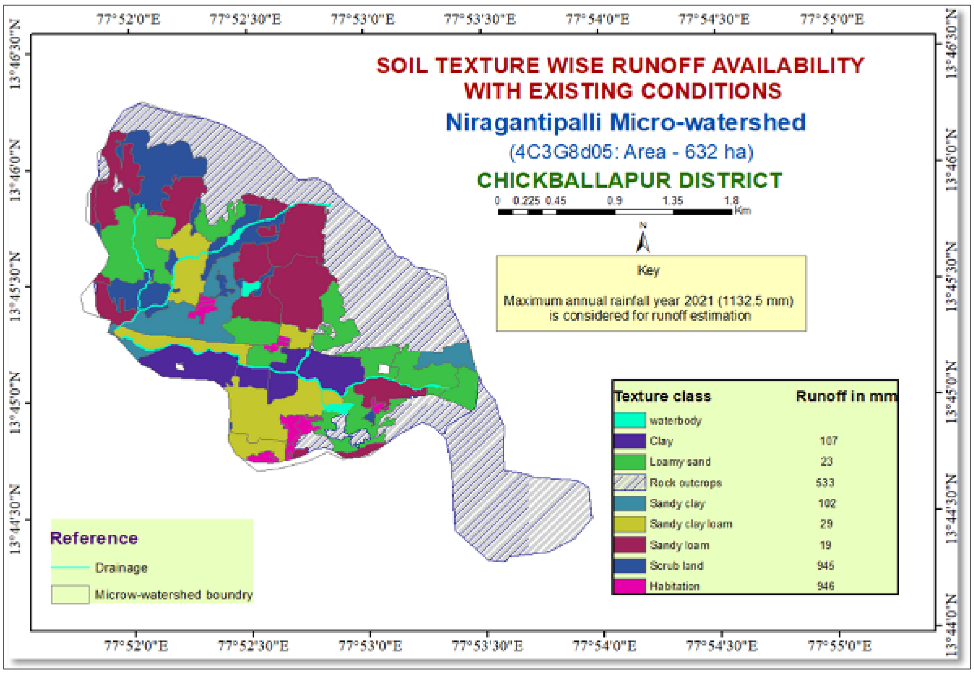

Fig. 10. Variations in runoff availability with existing conditions of the Niragantipalli micro-watershed during 2021.

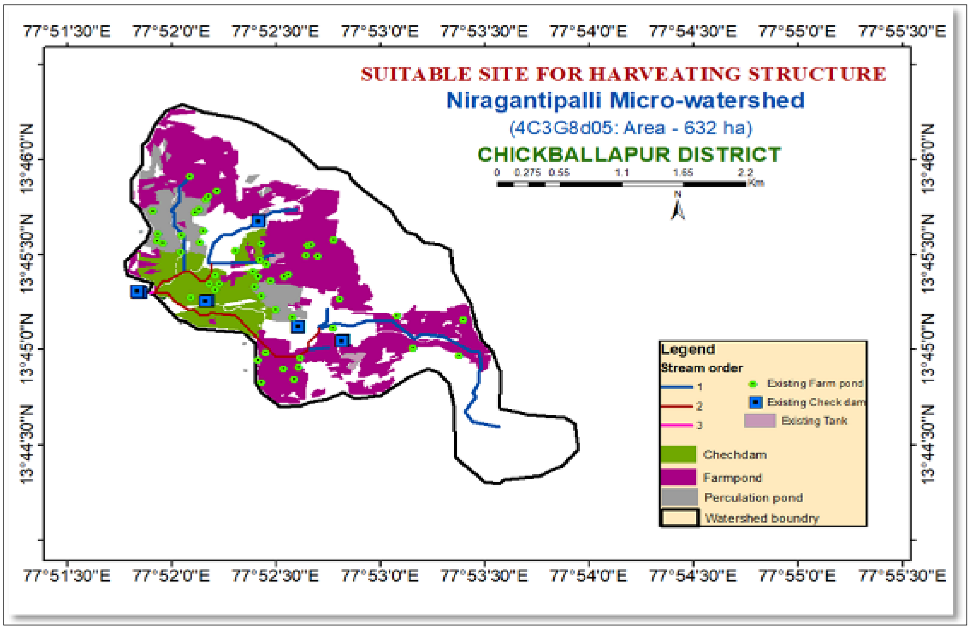

Fig. 11. Suitable sites for harvesting structures in Niragantipalli micro-watershed.

Table 7. Suitable area for water harvesting structures

Sl. No.	Rainwater harvesting structures	Area (ha)	Area (%)
1	Check dam	55.00	8.70
2	Farm pond	254.00	40.20
3	Percolation pond	63.46	10.00

55 ha (8.7% of the study area) and provide protective irrigation and groundwater recharge potential. Farm ponds, constructed as dugout ponds on relatively flat areas with low soil permeability, cover 40.2% of the area. In contrast, percolation ponds, which enhance groundwater recharge, are suitable for 10% of the study area (Table 8).

Various soil and water conservation measures were also recommended to improve soil moisture retention and reduce erosion based on the study area's topography and hydrology. Contour bunds, covering 152 ha (24.5% of the area), are the most extensive measure and are effective in slowing surface runoff and reducing soil erosion. Following natural land contours, these bunds facilitate increased infiltration and soil moisture retention. Staggered trenches, covering 29.68 ha (4.7% of the area), provide complementary erosion control on steeper slopes by disrupting water flow and capturing sediments, thereby improving soil stability. Additionally, V-shaped ditches, which cover 32.54 ha (5.14% of the area), are implemented in areas with high runoff potential, as shown in Fig. 12. These ditches direct and capture runoff, promoting infiltration while mitigating the risk of gully erosion.

The study highlights that well-placed water harvesting structures, coupled with soil conservation practices, can effectively enhance water storage and reduce surface runoff. These structures not only contribute to irrigation and groundwater recharge but also support sustainable agricultural practices. These findings are in line with the results of previous studies (30, 31)

Table 8. Suitable area for soil and water conservation structures

	Soil and water conservation structures	Area (ha)	Area (%)
4	Contour bund	152.00	24.50
5	Staggered trenches	29.68	4.70
6	V-shaped ditch	32.54	5.14
7	Continuous trench bund	52.83	8.35

Conclusion

The combined application of water harvesting and conservation techniques addresses immediate water storage needs and long-term soil health, providing a holistic approach to water and land resources management. This approach has proven effective based on the characteristics of the study area. The results indicate that 40.20% of the study area is primarily suitable for farm ponds, while 24.50% is primarily suitable for conservation measures such as contour bunds. Additionally, integrating GIS-based planning with community participation can enhance the sustainability of these interventions, significantly contributing to agricultural productivity and environmental stability.

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Authors' contributions

BN collected data, prepared various maps to interpret the results and wrote the original manuscript draft. KS supervised and assisted in software skills for data analysis and visualizing the data. D assisted in data analysis and methodology formation and reviewed and edited the manuscript. All authors read and approved the final manuscript.

Compliance with ethical standards

Conflict of interest: Authors do not have any conflict of interest to declare.

Ethical issues: None

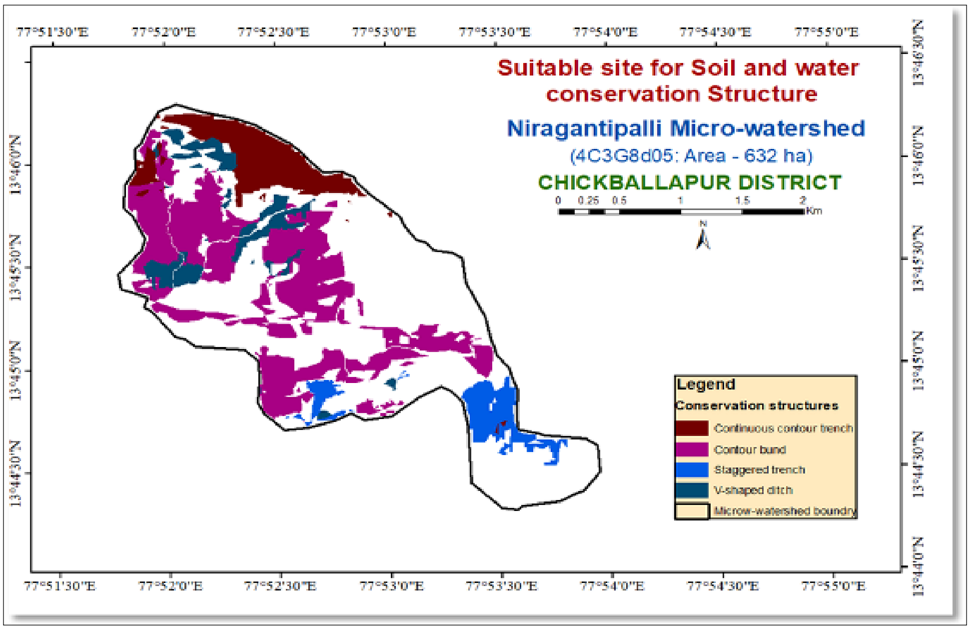

Fig. 12. Suitable sites for soil and water conservation structures in Niragantipalli micro-watershed.

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